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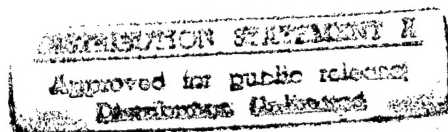
**The loudness of impulse and road-  
traffic sounds in the presence of  
masking background noise**

author

J. Vos

date

4 September 1996



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auteur : Dr. J. Vos  
datum : 4 september 1996  
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Uit onderzoek met in achtergrondruis aangeboden sinustonen is gebleken dat voor lage geluidsniveaus (tot ongeveer 10–15 dB boven de maskeerdrempel), de toename van de *luidheid* met geluidsniveau aanzienlijk groter was dan die van dezelfde in volledige stilte aangeboden tonen. Indien het geluidsniveau van de tonen ca. 30 dB hoger was dan de maskeerdrempel was de toename in de luidheid voor tonen in achtergrondruis echter vrijwel gelijk aan die voor tonen in stilte. Om na te gaan in hoeverre de eerder bepaalde relaties tussen geluidsniveau en *geluidhinder* van impuls- en wegverkeersgeluid door deze specifieke maskeereffecten zijn beïnvloed, werd het onderzoek naar de luidheid van *sinustonen* in achtergrondruis uitgebreid naar dat van *breedbandige* geluiden in achtergrondruis. De onderzochte breedbandige geluiden waren afkomstig van een pistoolschot (P), een detonerende handgranaat (H) en een voorbijrijdende personenauto (C). De luidheid van P, H en C werd bepaald in aanwezigheid van een (eveneens breedbandig) achtergrondlawaai met een laag en een hoog geluidsniveau.

Voor de condities waarin het geluidsniveau van het achtergrondlawaai, net als in de eerdere studie naar de geluidhinder, 30 dBA bedroeg, kwam de toename van de luidheid van de in het achtergrondgeluid aangeboden geluiden vrijwel overeen met die van de geluiden in stilte. Onder de aanname dat de hinder op z'n minst voor een deel door de luidheid wordt bepaald, werd dan ook geconcludeerd dat de relaties tussen het geluidsniveau en de hinder ten gevolge van impuls- en wegverkeersgeluid, zoals bepaald in aanwezigheid van een qua spectrum en niveau vergelijkbaar achtergrondgeluid, niet beïnvloed kunnen zijn geweest door de in de eerste alinea beschreven onevenredig sterke toename van de luidheid.

Voor de condities waarin het geluidsniveau van het achtergrondlawaai 55 dBA bedroeg en het geluidsniveau van de geluiden laag was, werd de luidheid van P gematigd, en die van H en C aanzienlijk gereduceerd. Gemiddeld genomen was deze reductie door de versnelde toename van de luidheid met het geluidsniveau geheel verdwenen vanaf geluidsniveaus die tenminste ca. 25 tot 35 dB boven de maskeerdrempel lagen. Dit komt overeen met reeds eerder in de literatuur beschreven resultaten voor gedeeltelijk gemaskeerde sinustonen.

Na correcties van het spectrale niveau konden de huidige resultaten tamelijk goed door een enigszins aangepaste versie van het onder andere in ISO 532B beschreven luidheidsmodel van Zwicker worden voorspeld: Globaal gezien kwam het voorspelde verloop in de luidheid overeen met de experimentele resultaten, en waren de verschillen niet groter dan 5–10 dB.

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Voor de condities waarin het geluidsniveau van het achtergrondlawaai, net als in de eerdere studie naar de geluidhinder, 30 dBA bedroeg, kwam de toename van de luidheid van de in het achtergrondgeluid aangeboden geluiden vrijwel overeen met die van de geluiden in stilte. Onder de aanname dat de hinder op z'n minst voor een deel door de luidheid wordt bepaald, werd dan ook geconcludeerd dat de relaties tussen het geluidsniveau en de hinder ten gevolge van impuls- en wegverkeersgeluid, zoals bepaald in aanwezigheid van een qua spectrum en niveau vergelijkbaar achtergrondgeluid, niet beïnvloed kunnen zijn geweest door de in de eerste alinea beschreven onevenredig sterke toename van de luidheid.

Voor de condities waarin het geluidsniveau van het achtergrondlawaai 55 dBA bedroeg en het geluidsniveau van de geluiden laag was, werd de luidheid van P gematigd, en die van H en C aanzienlijk gereduceerd. Gemiddeld genomen was deze reductie door de versnelde toename van de luidheid met het geluidsniveau geheel verdwenen vanaf geluidsniveaus die tenminste ca. 25 tot 35 dB boven de maskeerdrempel lagen. Dit komt overeen met reeds eerder in de literatuur beschreven resultaten voor gedeeltelijk gemaskeerde sinustonen.

Na correcties van het spectrale niveau konden de huidige resultaten tamelijk goed door een enigszins aangepaste versie van het onder andere in ISO 532B beschreven luidheidsmodel van Zwicker worden voorspeld: Globaal gezien kwam het voorspelde verloop in de luidheid overeen met de experimentele resultaten, en waren de verschillen niet groter dan 5–10 dB.

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Author: Dr. J. Vos

Institute: TNO Human Factors Research Institute  
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## SUMMARY

Research with *pure tones* presented in background noise has shown that for signal levels up to about 10–15 dB above masked threshold, the loudness growth is considerably higher than that of the same pure tones in quiet, whereas for signal levels higher than about 30 dB above masked threshold, the loudness growth for pure tones in background noise and pure tones in quiet is about the same. To establish to which extent previously determined relationships between sound level and annoyance caused by impulse and road-traffic sounds had been affected by the specific masking phenomena described above, the research on the loudness growth of *pure tones* in background noise was extended to that of *wideband* sounds in background noise. The wideband sounds included were produced by a pistol shot (P), a detonating hand-grenade (H), and a passing passenger car (C). The loudness of P, H, and C was investigated for a low and a high sound level of a wideband continuous background noise.

For the conditions in which the background noise was presented at the low level of 30 dBA, as was the case in the previous study on annoyance, the growth in loudness of P was equal to that of P presented in quiet. For H and C, the growth in loudness with sound level was slightly higher than that for the same sounds presented in quiet at very low levels (up to about 10 dB above masked threshold) only. On the assumption that annoyance is at least partly determined by loudness, it was therefore concluded that the relationships between sound level and the annoyance caused by impulse and road-traffic sounds presented against a low-level background noise, had not been affected by loudness recruitment.

For the additional conditions in which the background noise was presented at the higher level of 55 dBA, the loudness of low level P was moderately, and that of H and C considerably reduced. Overall, this loudness reduction disappeared at signal levels of about 25–35 dB above masked threshold, which is consistent with the results for pure tones, as reported in the literature. Differences in loudness growth, as obtained for P versus H and C, were related to spectral differences between these sounds. After corrections to the spectral levels that were related to the temporal envelopes of the signals, the results of the present experiment could be fairly well predicted by a slightly modified version of Zwicker's loudness model formalized in ISO 532B: The overall patterns in these predictions and the experimental results were the same, and the discrepancies were not greater than 5–10 dB.

## De luidheid van impuls- en wegverkeersgeluid in aanwezigheid van achtergrondlawaai

J. Vos

### SAMENVATTING

Uit onderzoek met in achtergrondruis aangeboden sinustonen is gebleken dat voor lage geluidsniveaus (tot ongeveer 10–15 dB boven de maskeerdrempel), de toename van de luidheid aanzienlijk groter was dan die van dezelfde in volledige stilte aangeboden tonen. De toename in de luidheid voor tonen in achtergrondruis was echter vrijwel gelijk aan die voor tonen in stilte indien het geluidsniveau van de tonen ca. 30 dB hoger was dan de maskeerdrempel. Om na te gaan in hoeverre de eerder bepaalde relaties tussen geluidsniveau en geluidhinder van impuls- en wegverkeersgeluid door deze specifieke maskeereffecten zijn beïnvloed, werd het onderzoek naar de luidheid van *sinustonen* in achtergrondruis uitgebreid naar dat van *breedbandige* geluiden in achtergrondruis. De onderzochte breedbandige geluiden waren afkomstig van een pistoolschot (P), een detonerende handgranaat (H) en een voorbijrijdende personenauto (C). De luidheid van P, H en C werd bepaald in aanwezigheid van een (eveneens breedbandig) achtergrondlawaai met een laag en een hoog geluidsniveau.

Voor de condities waarin het geluidsniveau van het achtergrondlawaai, net als in de eerdere studie naar de geluidhinder, 30 dBA bedroeg, kwam de toename van de luidheid van P overeen met die van P in stilte. Voor H en C was de toename van de luidheid alleen bij heel lage geluidsniveaus (tot ca. 10 dB boven de maskeerdrempel) iets groter dan die bij dezelfde geluiden in stilte. Onder de aanname dat de hinder op z'n minst voor een deel door de luidheid wordt bepaald, werd dan ook geconcludeerd dat de relaties tussen het geluidsniveau en de hinder ten gevolge van impuls- en wegverkeersgeluid, zoals bepaald in aanwezigheid van een qua spectrum en niveau vergelijkbaar achtergrondgeluid, niet beïnvloed kunnen zijn geweest door de in de eerste alinea beschreven onevenredig sterke toename van de luidheid.

Voor de condities waarin het geluidsniveau van het achtergrondlawaai 55 dBA bedroeg en het geluidsniveau van de geluiden laag was, werd de luidheid van P gematigd, en die van H en C aanzienlijk gereduceerd. Gemiddeld genomen was deze reductie door de versnelde toename van de luidheid met het geluidsniveau geheel verdwenen vanaf geluidsniveaus die tenminste ca. 25–35 dB boven de maskeerdrempel lagen. Dit komt overeen met reeds eerder in de literatuur beschreven resultaten voor gedeeltelijk gemaskeerde sinustonen.

Verschillen in de luidheidstoename, die tussen P enerzijds en H en C anderzijds werden gevonden, werden in verband gebracht met spectrale verschillen tussen deze geluiden. Na correcties van het spectrale niveau konden de huidige resultaten tamelijk goed door een enigszins aangepaste versie van het onder andere in ISO 532B beschreven luidheidsmodel van Zwicker worden voorspeld: Globaal gezien kwam het voorspelde verloop in de luidheid overeen met de experimentele resultaten, en waren de verschillen niet groter dan 5–10 dB.

## 1 INTRODUCTION

Several laboratory studies have shown that (1) at relatively low A-weighted equivalent levels ( $L_{eq}$ ), road-traffic sounds are rated to be less annoying than impulse sounds, and (2) the differences decrease with increasing  $L_{eq}$  of the sounds (Vos, 1990).

It is tempting to relate these findings to the results obtained in psychoacoustic research on loudness perception. As a result of presenting the sounds in continuous background noise, the thresholds of the impulse and road-traffic sounds to be rated were raised and their loudness reduced. Research with *pure tones* presented in wide- or narrow-band background noise has shown that the loudness reduction is highly dependent on the signal-to-noise ratio: The reduction is high at signal levels close to the masked threshold, and it decreases rapidly up to a level of about 30 dB above the effective threshold of the tone (Hellman, 1970; Hellman & Zwicker, 1964; Stevens & Guirao, 1967; Zwicker, 1963).

Stated differently, at signal levels up to about 10–15 dB above threshold, the loudness growth (recruitment) of sounds in background noise is considerably higher than that of the same sounds in quiet, whereas beyond about 30 dB above threshold, the loudness growth for sounds in background noise and sounds in quiet is about the same.

For comparable  $L_{eq}$ -values included in the experiments of Vos (1990), the sound levels of the individual vehicle passings were, relative to the masked threshold, lower than those of the individual impulses. As a result, the increase in loudness with sound level is expected to be higher for the vehicle passings than for the impulses. Since loudness at least partly determines the annoyance, it may be expected that the slope of the dose-response relationship for road-traffic sound is steeper than that for impulse sound. Qualitatively, this is in agreement with the experimental results.

To establish in a more quantitative way to which extent the convergence of the dose-response relationships for road-traffic and impulse sounds can be explained by loudness recruitment, we extended the research on the loudness of *sinusoids* in background noise to that of *wideband* sounds in background noise. In the experiment we used the sounds of a pistol shot, a detonating hand-grenade, and a passing passenger car. The background noise was a simulation of remote road-traffic sound characterized by very small fluctuations in sound level. Loudness was investigated for a low and a high level of the background noise.

## 2 METHOD

### 2.1 Stimuli

A pistol shot (P), a detonating hand-grenade (H), and a passing passenger car (C) served as distinct sound sources. Simulated remote road-traffic sound was used as the masking background noise (BN).



P was a digital recording of a pistol fired in a free-field condition. To avoid considerable differences in perceived stimulus duration between the signals presented in background noise and the signals presented in quiet, the sound of the original pistol shot, as well as those of the original detonating hand-grenade and vehicle passing, were faded out. For the period between 100 and 200 ms after the onset of the pistol bang, the amplitude of the original signal was linearly reduced from 100% to 0%, resulting in a final stimulus duration of 200 ms.

H was based on a digital recording performed at a distance of about 500 m. For the period between 0.5 and 1 s after the onset of the bang, the amplitude of the original signal was linearly reduced from 100% to 0%, resulting in a final stimulus duration of 1 s.

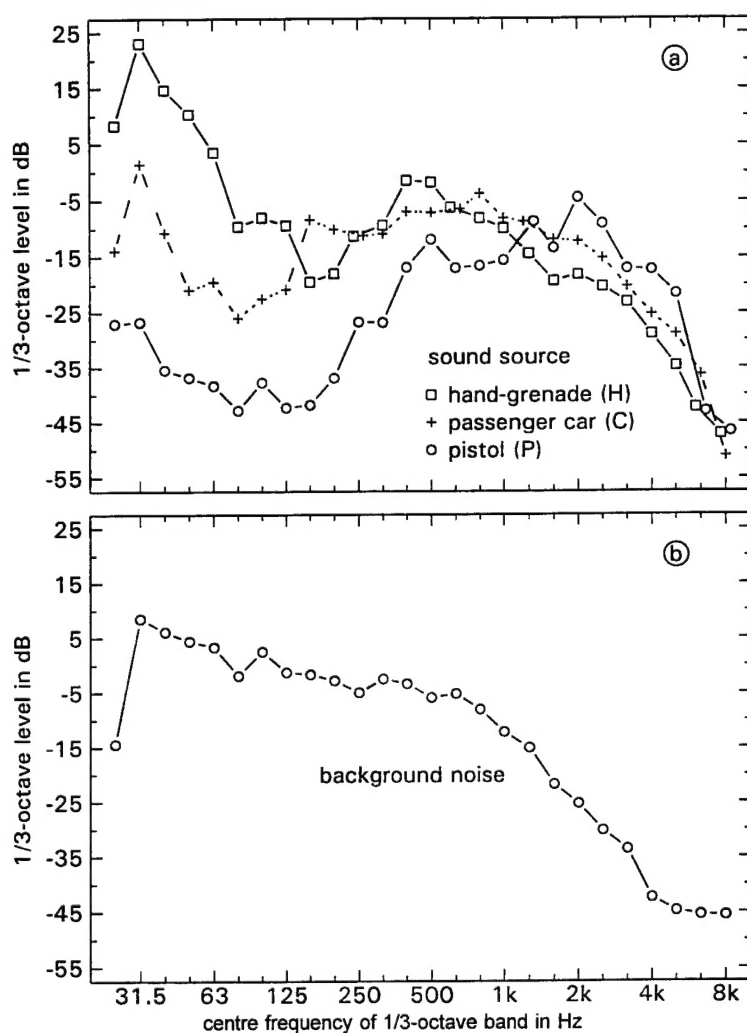


Fig. 1 (a) Spectra of impulse and vehicle sounds. (b) Spectrum of background noise. For both panels the maximum levels in the 1/3-octave bands are plotted relative to the overall A-weighted level. All spectra were measured at the ears of the subjects.

C was based on a recording of a Chrysler Voyager that was driven upon an asphalt road at a speed of 80 km/h. The distance between the recording microphone and the centre of the road was 15 m. At a distance of about 65 m ahead of the microphone the sound was faded in over a period of 650 ms. For the period between 2.25 and 3.25 s after the artificially generated onset, the signal was faded out. Again, shaping of the temporal envelope was performed by linear transformation of the amplitude from 0% to 100%, or vice versa.

BN was pink noise with a modified spectral envelope. The modification was determined by the spectral content of remote road-traffic sound characterized by very small fluctuations in sound level. The original road-traffic sound had been used in previous experiments (Vos, 1990, 1992; Vos & Geurtsen, 1987; Vos & Smoorenburg, 1985).

The sound spectra of P, H, and C, measured at the ears of the subjects, are shown in Fig. 1(a) relative to the overall A-weighted level of the sounds. These spectra were determined with a real time audio spectrum analyzer (Brüel & Kjær, type 2123) connected to a sound level meter (Brüel & Kjær, type 2218) mounted with a 0.5 in. microphone (Brüel & Kjær, type 4133). All spectra are based on the maximum levels in the 1/3-octave bands (integration time equal to 1/8 s). Fig. 1(a) shows that H is dominated by energy in bands with frequencies  $\leq 125$  Hz, P is dominated by energy in bands with frequencies between 800 and 6000 Hz, whereas C is characterized both by low and high frequency energy. Fig. 1(b) shows the spectrum of BN, expressed as the  $L_{eq}$  per 1/3-octave band, relative to the overall A-weighted  $L_{eq}$ . For frequencies between about 50 and 2000 Hz, the spectral envelope slope is equal to  $-3$  dB/oct, whereas for higher frequencies, the slope is equal to about  $-15$  dB/oct.

On the basis of A-weighted  $L_{eq}$  measurements within successive time periods (8 ms for P, 25 ms for H and C), temporal envelopes of the sounds were determined. After the relatively high level within the first milliseconds after the onset, the  $L_{eq}$  of P decreased at a rate of about  $-150$  dBA/s. For H, the relatively high peak had a duration of about 25–50 ms; after this peak the  $L_{eq}$  of H decreased at a rate of about  $-40$  dBA/s.

The in- and decrease of  $L_{eq}$  during the vehicle passing was relatively smooth and symmetrical. For example, the period during which the  $L_{eq}$  ranged between 10 dB below the maximum and the maximum lasted 1.6 s; the period during which the  $L_{eq}$  ranged between 20 dB below the maximum and the maximum lasted 2.5 s.

## 2.2 Apparatus

The experiment was run under the control of a personal computer (Compaq, type 386/E25) connected with a digital signal processor based on TMS-380. The P, H, and C sounds were reproduced by means of a digital-to-analog converter. These sounds passed a low-pass filter ( $-48$  dB/oct) with a cutoff frequency of 5 kHz. The BN masking sound was played on a DAT recorder (Luxman KD-117). The levels of the sounds were controlled by programmable attenuators. The mixed sounds were reproduced in a sound-proof room by means of a loudspeaker (B&O, type Beovox 5000). The distance between the loudspeaker and the head of the listener was about 2.5 m. For frequencies above 100 Hz, the reverberation time of the room ( $2.5 \times 4.5$  m) was shorter than 0.5 s.

### 2.3 Subjects

Six subjects, four males and two females, were tested over 8–10 half-day sessions, each session on a different day. Three were students from the University at Utrecht, who were paid for their participation; the other three were the author, a colleague, and a trainee. Before the experimental sessions, their hearing thresholds were determined with pure tones between 250 and 8000 Hz (Madsen MTA-86). For all subjects absolute thresholds (best ears) throughout the audiogram were below 5 dB HL (ISO/R 389, 1975).

### 2.4 Experimental design

The independent variables were (1) sound type (P, H, and C); (2) the level of the standard sound (in 5-dB steps; see Figs 3–8 for the adopted ranges); (3) the level of BN (30 or 55 dBA). Due to the nature of the experimental task, i.e. adjusting the level of a specific sound in quiet (or in BN) to that in BN (or in quiet) for equal loudness, two additional independent variables seemed to be relevant: (4) adjusting the sound level for equal loudness in quiet or in BN; and (5) the initial level of the sound to be adjusted (higher or lower than the level of the standard sound). Each condition was presented three times.

### 2.5 Procedure

After hearing levels had been tested, the subjects first started with a listening test in which detection thresholds were determined for one or two sounds, and with training series for the loudness adjustments. In total, detection thresholds were determined for nine different conditions: three conditions in which P, H, and C were presented in quiet, and six conditions in which these sounds were presented in BN at an  $L_{eq}$  of 30 or 55 dBA. These thresholds were determined in a 2-AFC paradigm. An adaptive procedure was used in which the level of the sound was decreased by 2 dB after three correct responses and increased by the same amount after an incorrect response. Each reversal of the direction of change in sound level over successive trials was counted as a turnaround. There were seven turnarounds. In the first run (a number of successive trials), however, the sound level was decreased by 3 dB after each correct response. The threshold was defined as the mean level on the trials that resulted in the last six turnarounds. This value estimates the level required to produce 79.4% correct responses in a nonadaptive 2-AFC procedure (Levitt, 1971).

The standard deviation (s.d.) of the sound levels for the last six turnarounds gave insight into the global performance of the subjects. Standard deviations greater than 4 dB occurred in less than 10% of the cases. If they occurred, the series was repeated until results with a standard deviation less than 4 dB were obtained. For each condition, thresholds were determined three times. The standard deviation of these three threshold determinations was considered as a measure of the reliability of the threshold. Overall, the standard deviation ranged between 0.2 and 2.7 dB ( $M=1.2$  dB,  $s.d.=0.7$  dB).

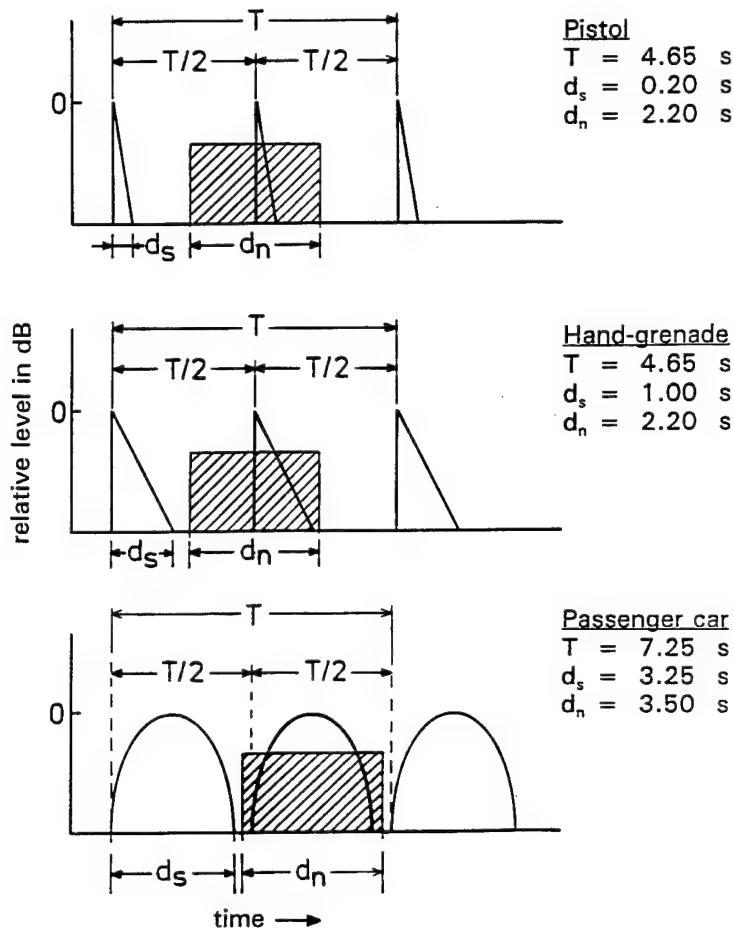


Fig. 2 Illustration of the temporal structure of the stimuli that were presented alternately in a repetitive cycle. The background noise stimulus is indicated by the shaded rectangle.

Basically, the procedure adopted to adjust the level of the comparison sound in such a way that it is perceived as loud as the standard sound was identical to that used by Stevens and Guirao (1967) and by Hellman *et al.* (1987), i.e., the sound in quiet and the sound in BN were presented alternately in a repetitive cycle (see Fig. 2). For the conditions in which the loudness of P and H was investigated, the repetition time was 4.65 s, and the onsets of the sounds in quiet and in BN were presented in strict isochrony. BN had a duration of 2.2 s, it started 1.1 s before the onset of the relevant sound, implying that the onset of the sound coincided with the centre of BN. For the conditions with C, the repetition time was 7.25 s. BN had a duration of 3.5 s and it started 125 ms before and ended 125 ms after the physical on- or offset of the relevant C sound. For C, the time between the onset of BN and the moment at which the level of the vehicle sound was  $-20$  dB relative to the maximum, was equal to 0.5 s.

Also the instructions to the subjects were similar to those of Stevens and Guirao (1967). The subjects adjusted the level of the comparison sound by pressing the relevant keys of a response box. The minimum step size was 1 dB. When the subjects were satisfied with the adjustment, they pressed a ready-button.

A series comprised various levels of the standard sound, ranging from 10 dB up to typically 30–75 dB above the detection threshold in quiet; the upper limit was dependent upon sound type and the level of BN. The presentation order of the conditions within a series was randomized. A block comprised four series, which were different with respect to (1) whether the standard sound was presented in quiet or in BN, and (2) whether the loudness of the comparison sound at the beginning of the cycle was clearly lower (ascending series) or clearly higher (descending series) than that of the standard sound.

There were six different blocks, one for each combination of sound type and the level of BN. The presentation order of the different blocks was balanced according to a  $6 \times 6$  Latin square. Also the presentation order of the four series within a block was balanced. In the first series, all conditions were presented twice. After completion of the six blocks, the third replica was presented. Presentation order of these conditions was similar to that of the previous conditions.

### 3 RESULTS

The results were expressed as the A-weighted sound exposure level (ASEL) at which the comparison and standard sounds were perceived equally loud. For a 30-dB range in the level of the standard sound, the data obtained with BN at an  $L_{eq}$  of 30 dBA were subjected to an ANOVA [6 (subjects)  $\times$  3 (sound type)  $\times$  2 (adjusting the comparison sound in quiet or in BN)  $\times$  7 (the level of the standard sound)  $\times$  2 (ascending or descending series)  $\times$  3 (replica), all repeated measures]. The results showed that the mean of the adjustments in the ascending series was 0.6 dB lower than that in the descending series [ $F(1,5)=6.53$ ,  $p=0.05$ ], and that there were no significant differences between the replicas ( $p>0.34$ ).

A similar ANOVA, with 5 instead of 7 different levels of the standard sound, was performed on the results obtained with BN at an  $L_{eq}$  of 55 dBA. The results showed that neither the main effect of the initial level of the comparison sound ( $p>0.09$ ) nor that of replication ( $p>0.17$ ) was significant. Consequently, we decided to collapse the data for these two variables.

#### 3.1 Conditions with the background noise level of 30 dBA

*Signal P.* Fig. 3 shows the results for P presented in background noise at a level of 30 dBA, for each subject separately. In this figure, ASEL of P in quiet is plotted as a function of the level of P in BN with the same loudness, and with the kind of comparison sound as a parameter. The oblique dashed line is given as a reference; if all data points were to coincide with this line, the presence of BN would have had no effect at all. The individual detection thresholds, one for P in quiet and one for P in BN, are represented by filled squares.

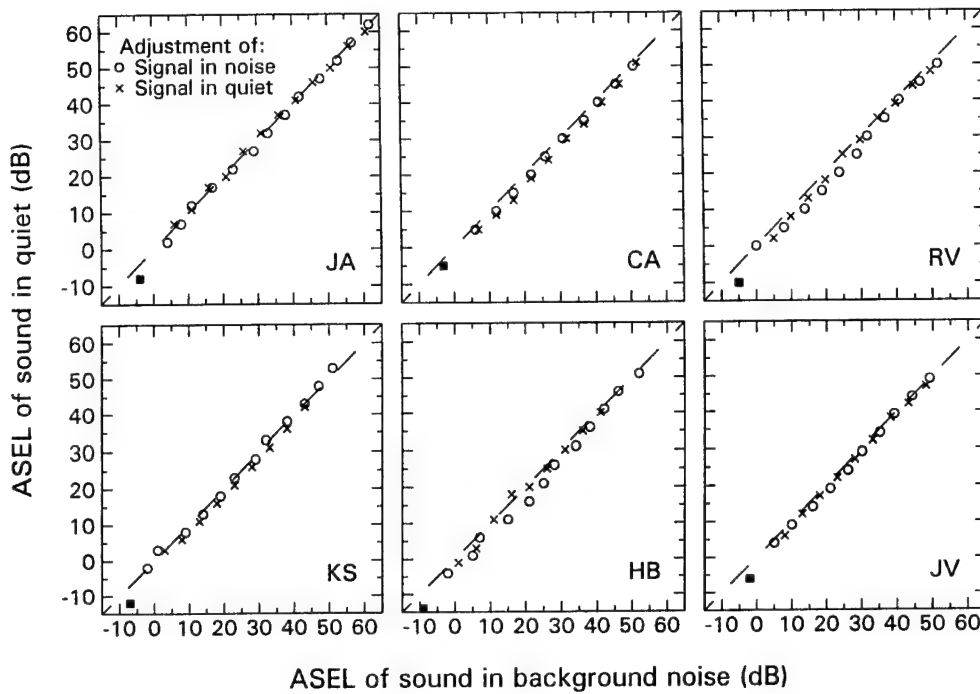


Fig. 3 ASEL of the pistol sound (P) in quiet as a function of the level of the equally loud sound in background noise, and with the kind of comparison sound as a parameter, for each subject separately. The level of the background noise was 30 dBA.

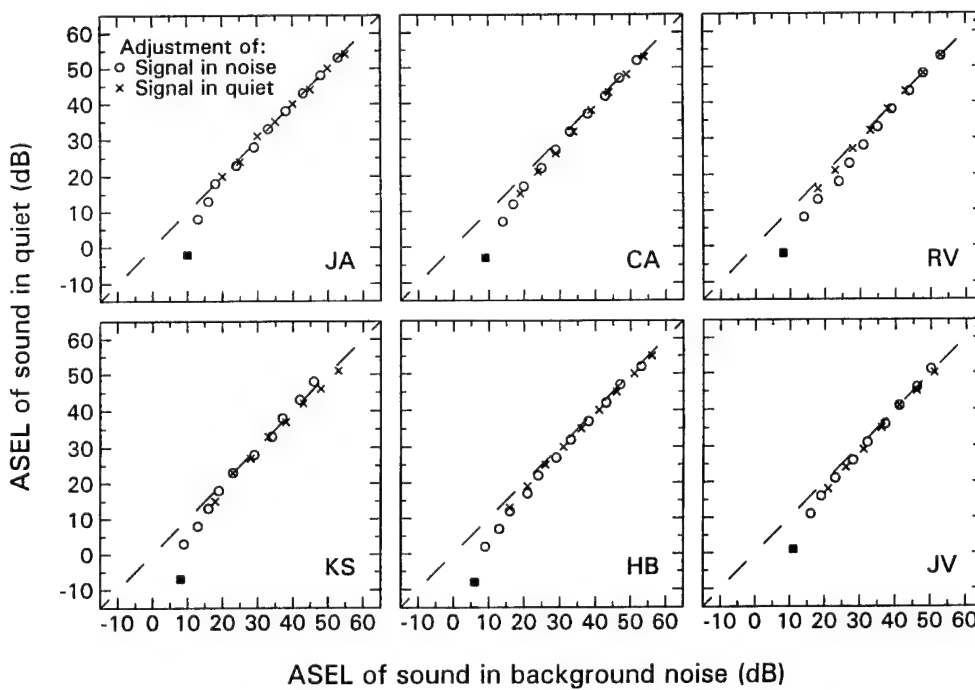


Fig. 4 As in Fig. 3, but now for the hand-grenade bang (H).

For four of the subjects (JA, CA, KS, and JV), none of the experimental results were significantly different from the reference line. For subjects RV and HB, the results significantly deviated from the reference line in a few conditions. These effects, however, were not systematically related with the level of the sounds. Overall, we conclude that for P, the growth in loudness was not affected by the presence of the low level BN.

*Signal H.* The experimental results for H are given in Fig. 4. For all subjects, the loudness of H presented in BN was reduced in the conditions in which ASEL was low, whereas for high levels, the results were not different from the reference line. For subject JA, the overall effect was less prominent than it was for the other five subjects. The statistical significance of the deviations was determined with the help of *t*-tests in which the estimated standard error of the mean was based on the six individual adjustments [2 (initial level of the comparison sound)  $\times$  3 (replication)]. For subject JA only the lowest data point (Fig. 4) was significantly different from the reference line ( $t=5.3$ ,  $p<0.005$ ). For the other five subjects, the first three up to five conditions with low ASELs were different from the reference line at significance levels of  $p<0.005$  or  $p<0.001$ . Overall, the loudness reduction of H in BN was about the same for the conditions in which the signal in noise or the signal in quiet was adjusted.

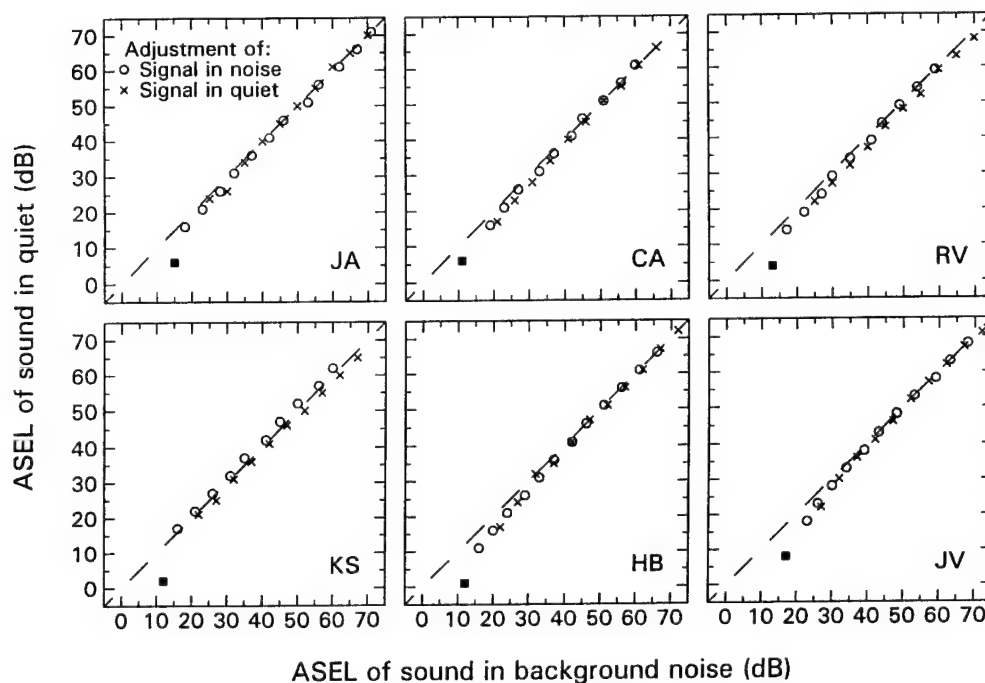


Fig. 5 As in Fig. 3, but now for the vehicle passing (C).

*Signal C.* The experimental results for C are given in Fig. 5. For four of the subjects (CA, RV, HB, and JV), the loudness of C presented in BN was slightly reduced in the conditions in which ASEL was low. For the lowest 10-dB range of conditions, the overall effect was equal to about 3–4 dB, and due to the small variance in the adjustments, statistically significant at a level of .005 or .001. Overall, the results obtained in the conditions in which

the level of the signal in noise was adjusted were not different from those in which the level of the signal in quiet was under the subject's control.

### 3.2 Conditions with the background noise level of 55 dBA

*Signal P.* The individual results for P presented in background noise at a level of 55 dBA are shown in Fig. 6. For a wide range of the level of P in BN, the loudness was reduced. For subjects JA and RV, the results were significantly lower ( $p$ -values between .01 and .001) than the reference line for the lower 30 dB range, whereas for subjects CA, HB, and JV, significant differences were obtained for the lower 40–50 dB range. Within the stimulus ranges indicated, the amount of loudness reduction was not or only slightly dependent on signal level. For subject KS, a consistent loudness reduction of P in BN was only found for ASELs between 5 and 15 dB.

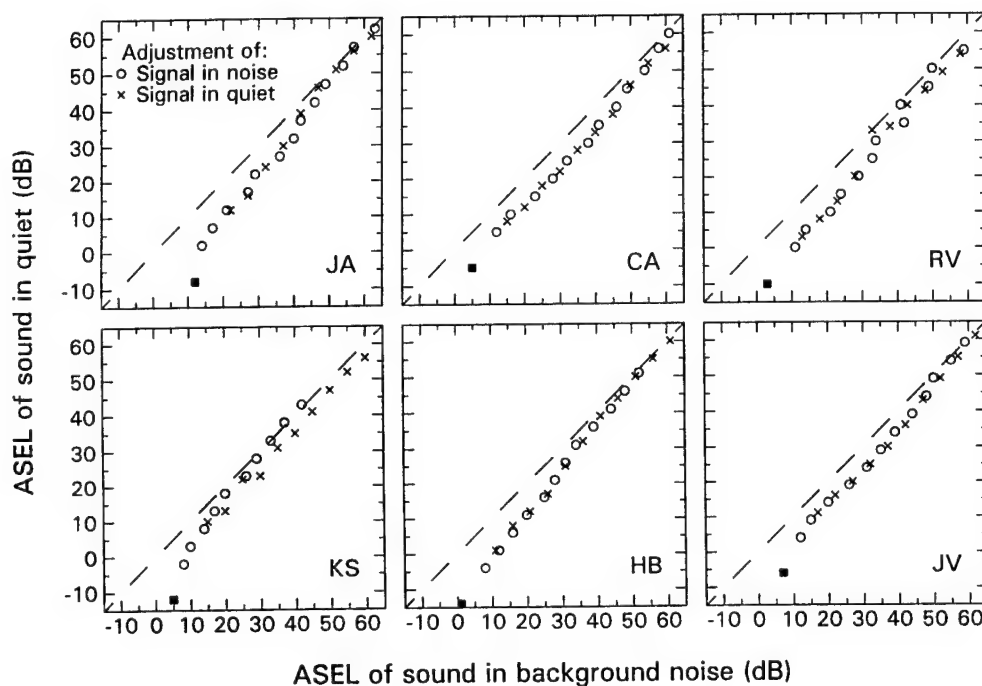


Fig. 6 ASEL of the pistol sound (P) in quiet as a function of the level of the equally loud sound in background noise, and with the kind of comparison sound as a parameter, for each subject separately. The level of the background noise was 55 dBA.



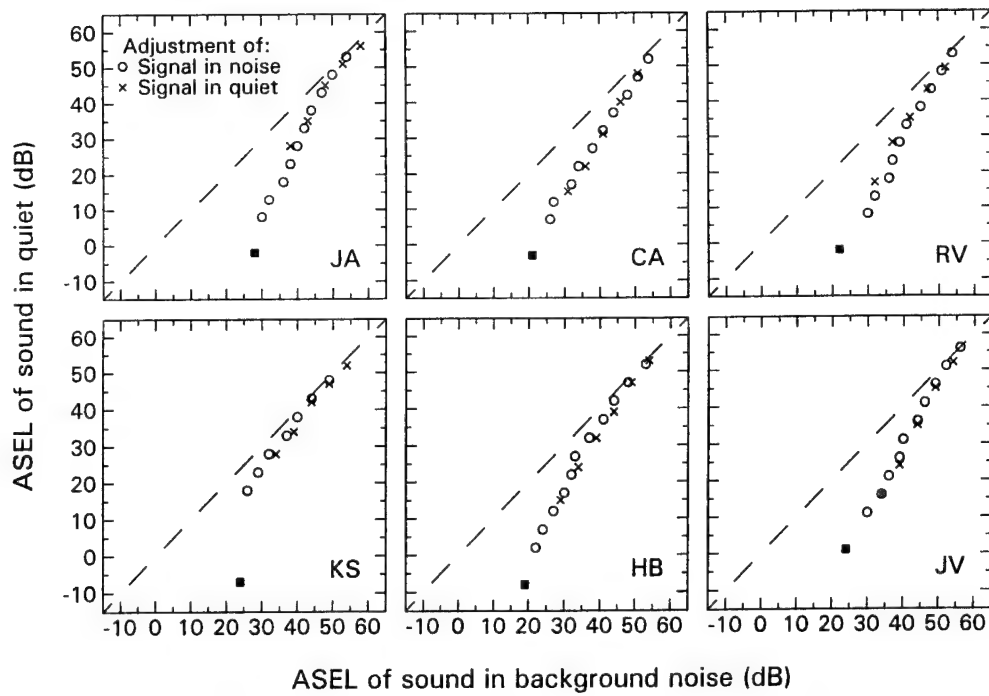


Fig. 7 As in Fig. 6, but now for the hand-grenade bang (H).

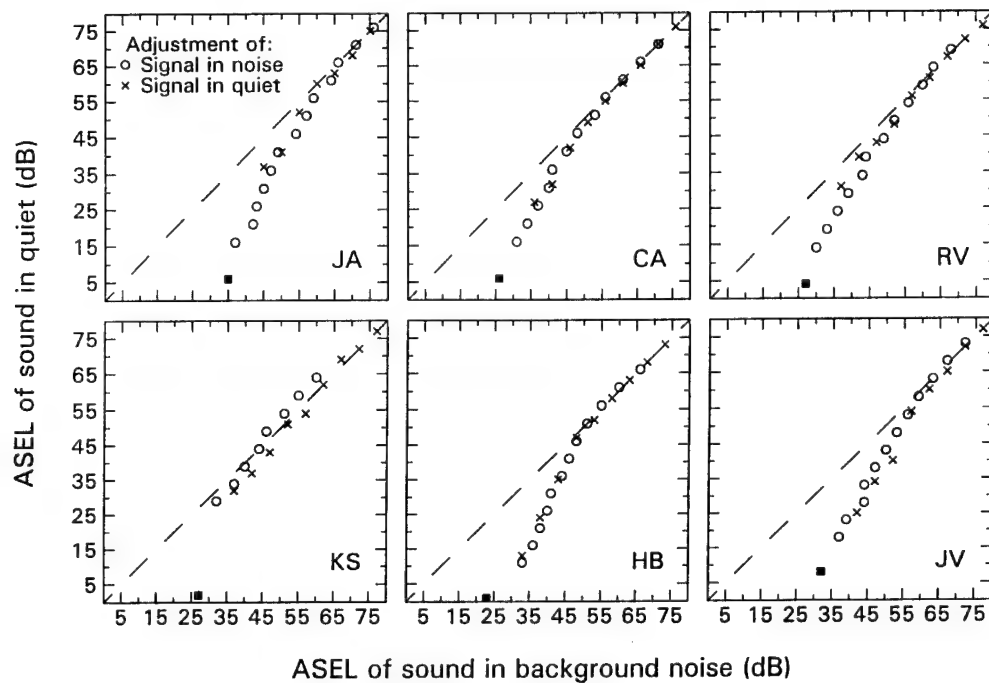


Fig. 8 As in Fig. 6, but now for the vehicle passing (C).

*Signal H.* The experimental results for H are given in Fig. 7. With the exception of subject KS, the loudness reduction of H in BN was highly dependent on the level of H. Starting from the detection thresholds, the loudness reduction gradually diminished within a stimulus range of about 25–35 dB. For subject KS, the loudness reduction was already resolved at a signal level of about 15 dB above threshold.

*Signal C.* The experimental results for C are given in Fig. 8. Again, for five of the six subjects, the loudness reduction of C in BN was highly dependent on the level of C. Starting from the detection thresholds, the loudness reduction gradually diminished within a stimulus range of about 20–30 dB. For subject KS, the presence of BN had no systematic effect on the loudness of partially masked C.

#### 4 PREDICTIONS BY ZWICKER'S LOUDNESS MODEL

It is interesting to determine to which extent the present results can be predicted by loudness models. As a first step, the ISO 532B-version of Zwicker's loudness model was selected. To enable the computation of the loudness of sounds presented in background noise, the ISO 532B-version was slightly modified.

Quite recently, an extensive revision of Zwicker's loudness model has been reported by Moore and Glasberg (1996). Since, at present, the latter revision is considered less suitable for impulsive sounds and for sounds with strong frequency components below 50–100 Hz (Moore & Glasberg, 1996; Glasberg, 1996), the loudness computation will be restricted to the slightly modified version of ISO 532B.

##### 4.1 Modification of computer program ISO 532B

Zwicker's model on loudness summation describes how the loudness of a complex sound depends upon its physical parameters. In Zwicker's model (e.g., see Zwicker & Scharf, 1965), five steps may be distinguished: 1) determination of the excitation pattern of the stimulus, 2) correction of the excitation pattern for transmission characteristics of the middle ear, 3) conversion of the excitation pattern from a logarithmic frequency scale into critical bands, 4) determination of the specific loudness for each critical band, and 5) determination of the overall loudness of the total sound by integration of the specific loudnesses.

For the calculation of the overall loudness, a graphical procedure has been described in an International Standard (Method B of ISO R-532, 1975), and to enhance its applicability, computer programs were published (Paulus & Zwicker, 1972; Zwicker *et al.*, 1984, 1991).

For sounds in quiet, the specific loudness,  $N'$ , is given by

$$N' = N'_{gr,0} \cdot \left( \frac{E_{gr}}{E_0} \right)^k \cdot \left[ \left( \frac{E_s}{E_{gr}} + (1-s) \right)^k - 1 \right], \quad (1)$$

in which  $N'_{gr,0}$  is an arbitrary constant that determines the units in which the specific loudness is measured,  $E_0$  is the excitation corresponding to  $I_0 = 10^{-12}$  Watt/m<sup>2</sup>,  $E_s$  is the excitation produced by the signal within a specific critical band,  $E_{gr}$  is the excitation produced within a specific critical band by an inaudible physiological background noise,  $s$  is a correction to account for the fact that the extent to which the masking threshold of a signal is lower than the level of the masker, is frequency dependent, and  $k$  is a constant set to 0.23.

In the present study, the loudness of the sounds in BN is compared with the loudness of sounds in quiet. In line with Van Meurs and Miedema (1985), the specific loudness of sounds in BN may be computed with the help of a slightly modified version of Eq. (1):  $E_{gr}$  within a specific critical band has to be changed into the maximum of the excitation ( $E_{max}$ ) produced by the physiological background noise and the excitation produced by the masking sound ( $E_m$ ).

However, when the excitation at threshold is produced by an external masking noise, the loudness of a signal in background noise increases more rapidly with level than when the threshold excitation is produced by internal noise (Zwicker & Scharf, 1965). More than three decades ago, Zwicker (1963) already suggested to correct the specific loudness with an empirically determined factor. This factor is dependent on both  $E_m$  and the difference,  $\Delta L$ , between  $E_s$  and  $E_m$ . Details about  $f(E_m, \Delta L)$  are given in the Appendix. Consequently, the formula for the computation of the specific loudness of sounds in background noise ( $-3 < \Delta L < 35$  dB) is given by

$$N' = f(E_m, \Delta L) \cdot N'_{gr,0} \cdot \left( \frac{E_{max}}{E_0} \right)^k \cdot \left[ \left\{ \frac{E_s}{E_{max}} + (1-s) \right\}^k - 1 \right]. \quad (2)$$

The power of Eq. (2) was tested by Van Meurs and Miedema (1985) for a 1000 Hz tone presented in broadband noise. In general, the overall loudness of the sinusoid in noise could be satisfactorily predicted.

An alternative procedure to estimate the specific loudness of sounds in background noise is given in Zwicker (1987a, 1987b).

#### 4.2 A comparison with our experimental results in an absolute sense

With the help of the modified computer program described above, we determined the loudness of P, H, and C presented in quiet and presented in background noise at a level of 30 and 55 dBA. For the various levels of the sounds in BN, the phon-values were converted to levels of the corresponding sounds in quiet with the same loudness (i.e., with the same phon-values).

The levels of the sounds at which the phon-values, as predicted by the loudness model, started to increase, did not coincide with the mean thresholds obtained in the experiments. For example, for H in BN presented at 30 dBA [Fig. 9(b)], ASELs  $\leq 16$  dB all yielded a loudness of 4 phon, and for H presented in the 55 dBA background noise [Fig. 10(b)], ASELs  $\leq 33$  dB all yielded the same loudness of 3 phon. The implications of these discrep-

ancies will be discussed in § 4.3. The present section focuses on those conditions in which the loudness model yielded phon-values higher than the threshold.

#### 4.2.1 Loudness of the signals presented in background noise at a level of 30 dBA

For BN at a level of 30 dBA the results are shown in Fig. 9. The experimental data, averaged across the six subjects (see Figs 3–5), are given as a reference.

The overall relation between the loudness of P in BN and the loudness of P in quiet [Fig. 9(a)] is well predicted by the loudness model.

The loudness reduction of low-level H in background noise is overestimated by about 10 dB [Fig. 9(b)]. For higher levels, the loudness of H in BN is well predicted.

For C in BN [Fig. 9(c)], the model predicts the small loudness reduction to diminish within a stimulus range of about 30 dB, whereas the average experimental results showed that this reduction was already overcome within a 10 dB stimulus range.

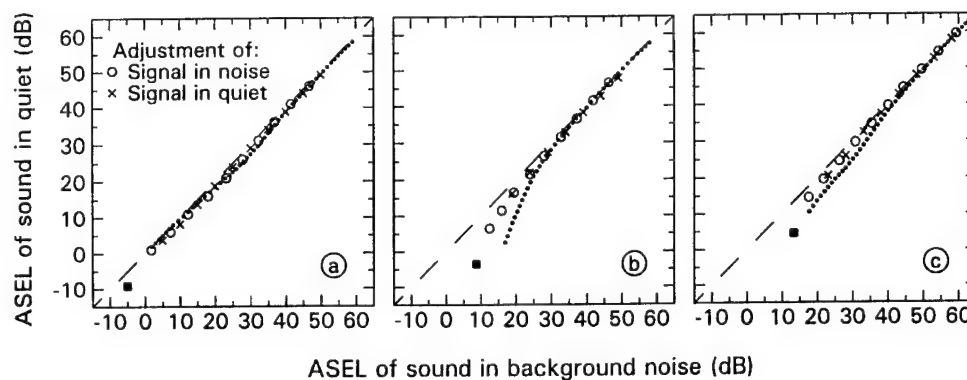


Fig. 9 ASELs of sounds in quiet as a function of the level of the equally loud sounds in background noise, as predicted by a slightly modified version of Zwicker's loudness model (dotted lines). The level of the background noise was 30 dBA. The experimentally obtained results, averaged across the six subjects, are given as a reference. Data are given for P, H, and C in panels (a), (b), and (c), respectively.

#### 4.2.2 Loudness of the signals presented in background noise at a level of 55 dBA

Fig. 10 shows the results for the conditions in which BN was presented at a level of 55 dBA. The experimental data, averaged across the six subjects (see Figs 6–8), are given as a reference.

For stimulus levels between 15 and 25 dB above masked threshold, the loudness reduction of P in BN [Fig. 10(a)] is overestimated by the model. The differences range between 5 and 10 dB. For higher levels, the loudness reduction is overestimated by 3–5 dB.

For H in BN [Fig. 10(b)] the loudness reduction is considerably overestimated. At a stimulus level of 10 dB above masked threshold, the difference is equal to 20 dB, and at a stimulus level of 20 dB above masked threshold, this difference is reduced to 10 dB. For higher levels, the loudness reduction of H in background noise is overestimated by about 3 dB.

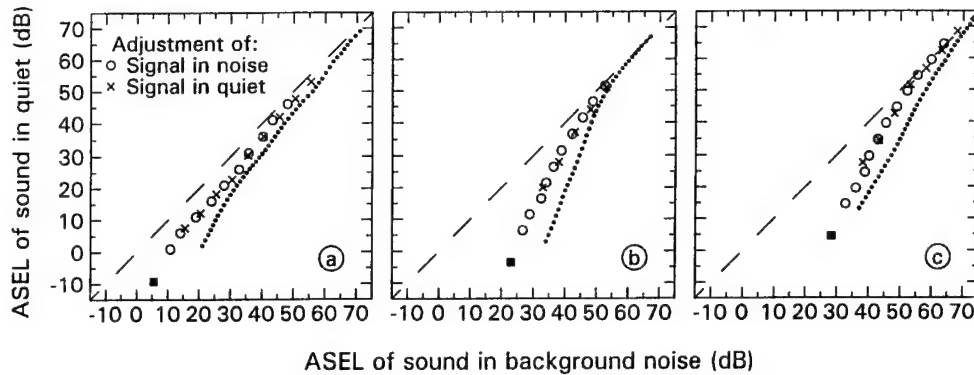


Fig. 10 ASELs of sounds in quiet as a function of the level of the equally loud sounds in background noise, as predicted by a slightly modified version of Zwicker's loudness model (dotted lines). The level of the background noise was 55 dBA. The experimentally obtained results, averaged across the six subjects, are given as a reference. Data are given for P, H, and C in panels (a), (b), and (c), respectively.

Fig. 10(c) shows that the average loudness reduction of C in BN, as observed for stimulus levels between 10 and 30 dB above masked threshold, is overestimated by about 10 dB. Except for this systematic overestimation, the loudness growth is well predicted by the model. For higher levels, the discrepancy between the predictions and the experimental results is gradually reduced from 10 dB to 0 dB.

#### 4.3 A comparison with our experimental results in a relative sense

In § 4.2 it was noted that the comparison between model predictions and experimental results was hampered because a number of conditions with very low signal levels yielded identical phon-values. Table I shows the ASELs beyond which phon-values higher than the minimum value were obtained. For P in quiet, the experimentally obtained detection thresholds were 10.7 dB lower than the threshold predicted by the loudness model. For P in background noise, these differences equalled 6.5 dB and 14.5 dB in the low- and the high-level background noise conditions, respectively.

The threshold differences indicate that the ASELs underestimated the loudness of the signals. For more adequate predictions, the spectral levels should be increased. Since for P, and also for C, there was no monotonous increase in the differences with increasing level of the background noise ( $< 30$  dBA, 30 dBA, and 55 dBA), it was decided to increase the spectral levels with the mean differences for each signal type separately. As implied by the data given in Table I, the overall corrections were 10.6 dB, 7.3 dB, and 4.3 dB for P, H, and C, respectively. The correction is negatively related to, amongst other things, the rise time of the signals.

Table I A-weighted sound exposure level in dB for signals P, H, and C presented in quiet and in two conditions in which the signals were presented in background noise (BN), beyond which the loudness model gives phon-values higher than the minimum value. In addition, the table includes the mean detection thresholds obtained in the experiment. For each subset of data, also the differences between the thresholds are given.

| signal type |            | in<br>quiet | A-weighted<br>level of BN |       |
|-------------|------------|-------------|---------------------------|-------|
|             |            |             | 30 dB                     | 55 dB |
| P           | model      | 1.5         | 1.5                       | 20.0  |
|             | experiment | -9.2        | -5.0                      | 5.5   |
|             | difference | 10.7        | 6.5                       | 14.5  |
| H           | model      | 1.0         | 16.0                      | 33.0  |
|             | experiment | -3.5        | 8.7                       | 23.0  |
|             | difference | 4.5         | 7.3                       | 10.0  |
| C           | model      | 9.0         | 16.0                      | 34.0  |
|             | experiment | 4.5         | 13.3                      | 28.3  |
|             | difference | 4.5         | 2.7                       | 5.7   |

To sum up, the new predictions were obtained as follows: For a specific ASEL-value, (1) the corresponding spectral levels were increased by the relevant constant. From these corrected spectral levels, (2) the loudness model predicted the phon-value of the signal presented in a specific background noise condition. Next, (3) the ASEL of the corresponding sound in quiet with the same loudness (i.e., with the same phon-value) was determined. Finally, (4) this level was reduced by the relevant constant.

#### 4.3.1 Recalculated loudness for the 30-dBA background noise conditions

For BN at a level of 30 dBA the adjusted predictions are shown in Fig. 11. Again, the experimental data are given as a reference.

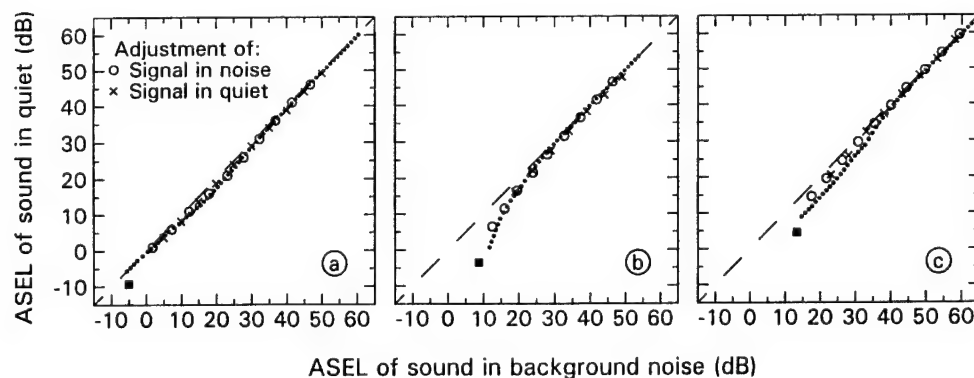


Fig. 11 Recalculated ASELs of sounds in quiet as a function of the level of the equally loud sounds in background noise, as predicted by a slightly modified version of Zwicker's loudness model (dotted lines). The level of the background noise was 30 dBA. The experimentally obtained results, averaged across the six subjects, are given as a reference. Data are given for P, H, and C in panels (a), (b), and (c), respectively.

The overall relation between the loudness of P in BN and the loudness of P in quiet [Fig. 11(a)] is well predicted, which is not surprising because a perfect prediction had already been obtained in the previous comparison.

Except for a small underestimation of the loudness of H in BN at a very low signal level [Fig. 11(b)], the loudness growth is very well predicted by the model.

For C in BN [Fig. 11(c)], the loudness reduction is slightly overestimated only for very low levels of C.

#### 4.3.2 Recalculated loudness for the 55-dBA background noise conditions

For BN at a level of 55 dBA, the adjusted predictions are shown in Fig. 12. For very low levels of P in BN [Fig. 12(a)], ranging between about 10 to 15 dB above masked threshold, the loudness is underestimated by 4–8 dB. For higher levels the newly predicted and the experimentally obtained results coincide.

For very low levels of H in BN [Fig. 12(b)], ranging between 5 dB and 10 dB above masked threshold, the loudness is underestimated by 5–10 dB. For levels of H higher than about 15 dB above masked threshold, the results are well predicted.

Fig. 12(c) shows that the average loudness reduction of C in BN, as observed for stimulus levels between 5 and 25 dB above masked threshold, is overestimated by about 5 dB. For higher levels, the discrepancy between the new predictions and the experimental results is gradually reduced from 5 dB to 0 dB.

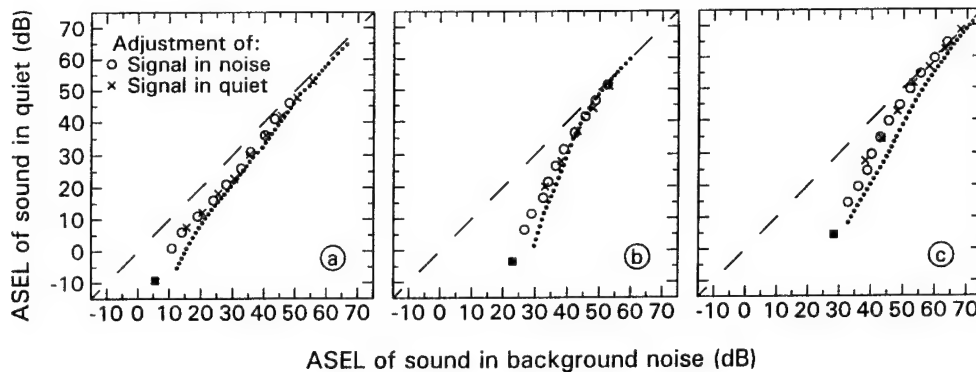


Fig. 12 Recalculated ASELs of sounds in quiet as a function of the level of the equally loud sounds in background noise, as predicted by a slightly modified version of Zwicker's loudness model (dotted lines). The level of the background noise was 55 dBA. The experimentally obtained results, averaged across the six subjects, are given as a reference. Data are given for P, H, and C in panels (a), (b), and (c), respectively.

## 5 DISCUSSION

### 5.1 Loudness recruitment and the level-dependent penalty for impulse sound

In the experiments reported by Vos (1990), the  $L_{eq}$  of the road-traffic sounds ranged from 30–33 to 60–65 dBA. The traffic sounds were 45 s in duration and comprised about 20 individual vehicle passings that could be (clearly) discriminated from the 30 dBA background noise. At an  $L_{eq}$  of 33 dBA, for example, the ASEL of 10 such vehicle passings varied between 28 and 35 dB, and for the other 10 passings, ASEL ranged from 36 to about 41 dB. In the present study, only for very low levels of the passenger car sound in BN (background noise masker presented at a level of 30 dBA) was the growth in loudness with sound level slightly higher than that for a similar sound presented in quiet [see Fig. 9(c)]. For ASEL higher than 30 dB, the growth in loudness was independent of the presence of the masker.

The ASEL of the individual impulse sounds presented in the experiments of Vos (1990) ranged from 32 to 59 dB. For the pistol shots in the present study [see Fig. 9(a)], the growth in loudness with sound level was independent of the presence of the masking sound for the entire range of levels investigated (ASEL between about 0 and 50 dB). For the detonating hand-grenades [see Fig. 9(b)], the growth in loudness was dependent on the presence of the masker for levels lower than 20 dB only.

From the results obtained in the present study, it must be concluded that for the road-traffic sounds investigated previously, it is very unlikely, and for the impulse sounds it is excluded that the relationship between sound level and annoyance had been affected by loudness recruitment. This all means that the level-dependent penalty for impulse sound, as found in several laboratory studies, cannot be accounted for by loudness recruitment.

### 5.2 Loudness recruitment predictions

In most conditions, the loudness reduction of the low-level signals presented in background noise, as predicted by the model from the (linear) SELs in the various 1/3-octave bands, was overestimated. By application of corrections to the spectral levels (§ 4.3), the degree of this overestimation could be significantly reduced.

In the 30-dBA background noise conditions, the overestimation in loudness reduction for H presented at a level of 10 dB above the detection or masked threshold was decreased from 10 dB to 0 dB. For C at the very low level of 5 dB above masked threshold, the discrepancy was reduced from 5 to 2 dB.

In the 55-dBA background noise conditions, the overall discrepancy between predictions and experimental results was reduced by about 5–10 dB.

The overestimation in loudness reduction for P presented at a level of 15 dB above masked threshold was decreased from 10 dB to about 5 dB, and for P at a level of 25 dB above masked threshold it was decreased from 5 dB to 0 dB.

For H at a level of 10 dB above masked threshold the overestimation in loudness reduction was decreased from 15 dB to 5 dB, and for a level of 15 dB above threshold it was decreased from 12 dB to 0 dB.



For C presented at levels between 10 dB and 25 dB above masked threshold, the overestimation in loudness reduction was decreased from 10 dB to 5 dB.

### 5.3 Loudness recruitment and spectral content

The loudness growth with level of H and C in BN was higher than that of P. In the conditions in which the level of BN was 55 dBA, the line that may be fitted to the results obtained for H [Fig. 10(b)] has a slope of about 1:2.3 dB, indicating that a 1-dB increase in the level of H in BN resulted in a loudness increase that corresponds to the same loudness increase produced by a 2.3 dB shift in the level of H in quiet. For C [Fig. 10(c)] and P [Fig. 10(a)], these slopes are equal to 1:2.1 dB and 1:1.4 dB, respectively.

These slopes may be related to the spectral content of the sounds. It was shown in Fig. 1(a) that the spectrum of H contained high-level components in the frequency range between about 25 and 63 Hz, whereas the spectrum of P contained high-level components between about 400 and 3000 Hz. The spectrum of C contained relevant components both in the low and in the high frequency bands.

The classical "equiloudness contours" (Robinson & Dadson, 1956) show that in the middle frequency range between about 250 and 4000 Hz, every 10 dB increase in the level of a sinusoid results in an increase in the loudness level of 10 phon. For very low frequencies between 20 and 50 Hz at relatively low sound-pressure levels, however, each 10-dB level increment results in an increase in the loudness level of almost 20 phon.

The differences in slopes between H, C, and P cannot simply be explained by the frequency-dependent effect on the loudness just described, because it applies both to the sounds in background noise and the sounds in quiet. However, there might be an interaction effect between the deviating loudness increase at low frequencies and the presence of the background noise.

## 6 CONCLUSIONS

For sounds presented in a low-level continuous background noise of 30 dBA, the growth in loudness with level was almost equal to that obtained for the same sounds in quiet. Only for sounds presented at a very low level and comprising relatively much energy in the low-frequency bands was the growth in loudness slightly higher than that for the sounds presented in quiet.

Consequently, the hypothesis that the relationships between sound level and the annoyance caused by similar impulse and road-traffic sounds, as determined in previous studies with a comparable background noise masker, had been affected by loudness recruitment, must be rejected.

For low-level sounds presented against a high-level background noise of 55 dBA, a considerable reduction in loudness was found, especially for the sounds with relatively much energy in the low-frequency bands.

Consistent with the results for sinusoids, as reported in the literature, the loudness reduction for the wideband sounds presented against the 55 dBA background noise, was resolved at signal levels of about 25–35 dB above threshold.

After corrections to the spectral levels, the results could be rather well predicted by a slightly modified version of Zwicker's loudness model. For low-level sounds presented in the 30-dBA and the 55-dBA background noise conditions, the discrepancies between predictions and experimental results were within 3 dB and within 5–10 dB, respectively. For signal levels higher than 20 dB above masked threshold, the predictions were typically equal to the results in both background noise conditions.

#### ACKNOWLEDGEMENTS

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Soesterberg, 4 September 1996

A handwritten signature in black ink, consisting of a large, stylized 'J' followed by a series of loops and a long horizontal stroke extending to the right.

Dr. J. Vos  
(author, project manager)

## APPENDIX

The loudness of a signal that is presented in an external noise increases more rapidly with level than when the threshold excitation is produced by internal physiological noise. To account for this discrepancy, Zwicker (1963) suggested to correct the specific loudness, as computed from his model, by an empirically determined factor. This factor is dependent on both  $E_m$  and the difference,  $\Delta L$ , between  $L_{Es}$  and  $L_{Em}$  in decibels. For  $L_{Em}=40$  dB per critical band, the factor-values given by Zwicker (1963) were summarized by Van Meurs and Miedema (1985) for  $(-3 < \Delta L < 35 \text{ dB})$  with the help of

$$f(L_{Em}=40\text{dB}, \Delta L) = 1.56 + 0.153\Delta L - 0.0165\Delta L^2 + 0.00055\Delta L^3 - 6.076(10^{-6})\Delta L^4 .$$

For  $\Delta L \geq 35$  dB,  $f(L_{Em}, \Delta L) = 1$ . In line with Van Meurs and Miedema (1985), it is assumed that  $f(L_{Em}=40\text{dB}, \Delta L)$  also applies for  $L_{Em} > 40$  dB and that for  $7 < L_{Em} < 40$  dB,  $f(L_{Em}=40\text{dB}, \Delta L)$  has to be weighted by  $(L_{Em}-7)/33$ .

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| 14. SUPPLEMENTARY NOTES  |   |  |
| 15. ABSTRACT (MAXIMUM 200 WORDS, 1044 BYTE)<br><p>Research with <u>pure tones</u> presented in background noise has shown that for signal levels up to about 10–15 dB above masked threshold, the loudness growth is considerably higher than that of the same pure tones in quiet, whereas for signal levels higher than about 30 dB above masked threshold, the loudness growth for pure tones in background noise and pure tones in quiet is about the same. To establish to which extent previously determined relationships between sound level and annoyance caused by impulse and road-traffic sounds had been affected by the specific masking phenomena described above, the loudness of <u>wideband</u> sounds in background noise was investigated. The wideband sounds included were produced by a pistol shot (P), a detonating hand-grenade (H), and a passing passenger car (C).</p> <p>For the conditions in which the background noise was presented at the low level of 30 dBA, as was the case in the previous study on annoyance, the growth in loudness of the various sounds was almost equal to that of those presented in quiet. On the assumption that annoyance is at least partly determined by loudness, it was therefore concluded that the relationships between sound level and the annoyance caused by impulse and road-traffic sounds presented against a low-level background noise, had not been affected by loudness recruitment.</p> <p>For the additional conditions in which the background noise was presented at the higher level of 55 dBA, the loudness of low level P was moderately, and that of H and C considerably reduced. Overall, this loudness reduction disappeared at signal levels of about 25–35 dB above masked threshold, which is consistent with the results for pure tones, as reported in the literature. After corrections to the spectral levels, the results of the present experiment could be fairly well predicted by a slightly modified version of Zwicker's loudness model formalized in ISO 532B: The discrepancies were not greater than 5–10 dB.</p> |   |  |
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